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Recognizing of Traveling Wave Patterns on Digital Substations for Automatic Reclosing of High-Voltage Overhead-Cable Power Lines Transmissions

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Abstract

The development of Smart Grid, Digital Substation concepts, is characterized by the complication of protection and automation systems, which requires the development and implementation of new algorithms of work. In this article there considered a new approach to the organization of automatic reclosing of high-voltage overhead-cable power lines transmissions in metropolitan areas, based on the recognizing of traveling wave processes due to a fault. There described the correlation method of estimation of traveling wave processes, which makes it possible to estimate the faulted section. There performed the simulation of faults at different sections of the overhead-cable power line, and its traveling wave patterns were obtained. There described the prospects for the development of the method and the direction of further research.

Keywords: Digital Substation, automatic reclosing, traveling wave pattern (TWP), digital signal processing (DSP), correlation analysis, simulation modeling, Smart Grid.

INTRODUCTION

Nowadays, digital technologies have penetrated into all branches of the human economic activity and have been a trend in the development of new concepts and technologies. Electric power industry is not an exception. In recent years a number of countries, as well as Russia, have been developing the Smart Grid, Digital Substation (DS), Virtual Power Plant concepts etc. Its implementation involves changing approaches to the organization of control systems of power facilities (power plants, substations etc.). Among other things, this change is characterized by the complication of relay protection and automation (RPA) systems, which requires the development and implementation of new algorithms of work of such systems.

One of the promising directions of RPA development is the development and implementation of the traveling wave based digital RPA (TWRPA), which is one of the ways to achieve the objectives of introduction of DS concept: improving the quality of function and operation of the substation. Quality can also be understood here as the basic requirements for RPA: reliability, selectivity, sensitivity, speed of action.[1].

Often, relay protection is positioned as a recognizing system, but so far no one has applied approaches to the estimation of electrical signals that are used in conventional recognition systems: recognition of speech, image (facial in particular), fingerprints etc. In order to do this, it is enough to take the tried-and-tested conventional theory of digital signal processing (DSP), which is used, as mentioned above, for the design of various automatic recognition systems, and apply it to the electrical signals estimation systems for RPA.

This approach is proposed to be used in particular for the construction of the TWRPA, based on the formation and recognizing of so-called "traveling wave patterns" (TWP) (the definition of the TWP will be given later). As the TWP is an analogue of, for example, waveform of acoustic oscillations, or image, it is expedient to use the theory of DSP of sound and image signals. It was decided to use the proposed approach to solve the problems of automatic reclosing of high-voltage overhead-cable power lines (AR of HVOCPL). The AR of HVOCPL device will be the first prototype, the principle of operation of which will be based on the proposed methods. This will make it possible to develop and test a number of technical solutions that can then be used to solve a wider range of tasks of TWRPA. The problem of AR of HVOCPL is relevant for a number of reasons that determined the decision to choose it as the object of research.

PROBLEMS OF AR OF HVOCPL

Nowadays, there is a tendency to install high-voltage overhead transmission lines underground in large cities. At the same time, often, the whole line doesn't present completely a

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cable, but the cable is inserted just in a certain sector. Thus, there are so-called mixed or overhead-cable power lines. This is due to the release of large areas reserved for the sanitary zone of overhead power lines, strong electromagnetic fields, harmful to the health of citizens, improving the esthetic of streets of cities, increasing the reliability and technological level of the city's energy system. During the implementation of this task, a number of technical problems arise. One of them is the need to perform the AR of HVOCPL, which is a measure of improving the reliability of power supply.

According to Electrical Installations Code (EIC) (7th edition (approved by the Order of the Ministry of Energy of 08.07.2002 No. 204) paragraph 3.3.2) there "... should be provided the automatic reclosing of overhead and mixed (overhead-cable) power lines of all types of voltages above 1 kV. The refusal to apply an AR should be justified on a case-by-case basis" [2].

The algorithms used for AR of overhead power lines are ineffective in the case of HVOCPL, as its operation can lead to significant damage and expensive repairs of the cable. Indeed, the repeated energisation of high-voltage cable lines (HVCL) passing through the residential area can cause significant damage, injury and even death of people. As a rule, there is no phenomenon of fault self-elimination on HVCL, and before re-energisation of the HVCL it must be tested. [3]

Therefore, at the fault on the cable section, the power line must not be re-energised. In this regard, for effective performance of automatic reclosing on such lines, it is necessary to determine with a high degree of accuracy which section (overhead or cable) is a faulted.

At the moment, there is only one technical solution of this problem, which has been developed during R & D work "Automatic reclosing with the power line monitoring function" [3]. In this solution it is proposed to determine the faulted section and the fault location using traditional methods based on comparison of the currents at the terminations of the cable section (differential method), on the evaluation of the emergency mode parameters, and on location methods (active probing method). These methods require the installation of additional equipment both at the substations and at the place of overhead-cable transition (current sensors, data collection and transmission device, GPS / GLONAS modules), communication channel organization, that is why it is unreasonably expensive solution and dangerous with regard to its maintenance [3].

In this relation, it is necessary to develop cheaper and more effective AR of HVOCPL device performing identification of the faulted section, which gives a permissive or prohibitory signal for the automatic reclosing cycle, which ensure the reliability of 110 kV and higher networks and minimize the costs of repairs.

The basic idea of the proposed solutions is to determine the faulted section on the basis of analysis of traveling wave process due to the fault, through special algorithms of DSP. This is possible because the behavior of the traveling wave process qualitatively and quantitatively depends on faulted section and fault location. The reason for this is a significant difference in the wave characteristics of the cable and overhead sections.

THE PRINCIPLES OF IMPLEMENTATION OF AUTOMATIC RECLOSING BASED ON THE RECOGNITION OF TWP

One of the promising directions of the development of relay protection and substation automation is TWRPA. These are devices, based on the recognizing of the traveling wave transient process behavior due to a fault.

As known, a fault causes the electromagnetic transient process, which can be divided into two stages with sharply different duration. The first (short) stage is characterized by the propagation of electromagnetic traveling waves through the electric network, this stage is often called the traveling wave process (TWP). There is a brief simplified description of this stage provided below [4].

Fault occurrence causes a reallocation of electromagnetic waves, as a result of which a "new" reflected wave begins to propagate from the fault location through the electrical network. Therefore, for convenience, the fault occurrence point can be considered as source of waves. When the wave (incident wave) arrive at the point of discontinuity (segment with different characteristic (or surge) impedance), such as other line terminations or busbars, part of the incident wave is reflected back along the line (reflected wave) and the other part is transmitted into and beyond the discontinuity (transmitted wave). During the wave propagation through the electric network at the point reached by wave at the current time, the current and voltage change rapidly (almost instantly), as a result of which high-frequency transient components appear in the signal [4, 6, 14, 15].

Therefore, by applying a high-pass filter or a bandpass filter with a sufficiently wide bandwidth, it is possible to extract the transient wave components (or transients), the appearance time of which corresponds to the traveling wave arrival time at the point of measuring. Fig. 1 shows the HVOCPL model, ladder (or lattice) diagram (the time diagram of traveling waves propagation along the line), as well as transients registered at the corresponding power line terminations [7 – 9, 11].

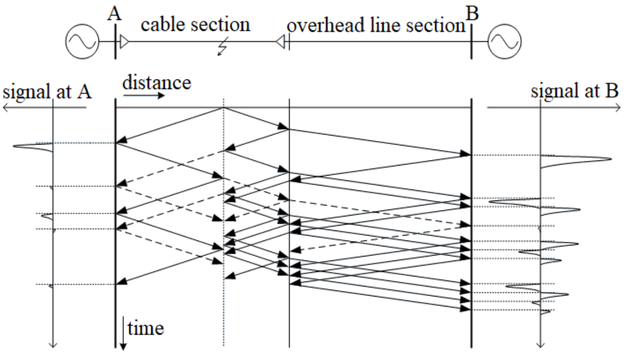

Figure 1: Formation of TWP

Depending on the faulted section and fault occurence point, traveling waves propagate through the electric network differently, reflecting and transmitting beyond the points of discontinuty (busbars, overhead-cable transition, branch line point etc.). Thus, transients measured at a certain point of the network, for a certain period of time, form a unique "traveling wave pattern" (TWP) for the given fault location and point of measurement.

By recognizing the obtained TWP it is possible to identify the faulted section (overhead line or cable) and give a permissive or prohibiting signal to the automatic reclosure, and also to determine the fault location with a high degree of accuracy.

MATHEMATICAL DESCRIPTION OF THE BASIS OF THE PROPOSED METHODS

One of the proposed methods for recognizing of TWP is based on the use of correlation functions. Correlation functions are used to characterize random processes. There is differentiation between autocorrelation and crosscorrelation functions [10]. In the theory of continuous random processes the autocorrelation function $R_{xx}(\tau)$ is a measure of the interconnection between the function $x(t)$ and the function $x(t+\tau)$, shifted with respect to $x(t)$ by the time τ [4]:

$$R_{xx}(\tau)=\lim_{T\to\infty}\left[\frac{1}{2T}\cdot\int_{-T}^{T}\big(x(t)\cdot x(t+\tau)\cdot dt\big)\right] \tag{1}$$

And the crosscorrelation function $R_{xy}(\tau)$ is a measure of the interconnection of two random time functions $x(t)$ and $y(t)$, defined as follows:

$$R_{xy}(\tau)=\lim_{T\to\infty}\left[\frac{1}{2T}\cdot\int_{-T}^{T}\big(x(t)\cdot y(t+\tau)\cdot dt\big)\right] \tag{2}$$

In the theory of DSP, correlation is used, for example, for speech recognition. In the case of discrete functions (signals), equations (1-2) can be written as follows [16]:

$$R_{xx}(n)=\frac{1}{N}\cdot\sum_{k=0}^{N-1}\big(x(k)\cdot x(n+k)\big) \tag{3}$$

$$R_{xy}(n)=\frac{1}{N}\cdot\sum_{k=0}^{N-1}\big(x(k)\cdot y(n+k)\big) \tag{4}$$

Using the crosscorrelation function of the two signals, the degree of its correspondence or "similarity" can be established. As an example, Fig. 2 shows three discrete signals *x, y1, y2*, let us determine the most similar one to the signal *x* via crosscorrelation functions. Fig. 3 shows the correlation functions $R_{xx}(\tau)$, $R_{xy1}(\tau)$, $R_{xy2}(\tau)$ computed for the corresponding signals of Fig. 2.

To simplify the understanding of compution of the correlation function it can be represented as follows: the first signal (*x*) is stationary (frozen) while the second signal (*y*) begins to move relative to the first signal with each new sample n and multiply each sample (*y*) by the corresponding sample (*x*) and then sum the products. Negative *n* corresponds to the shift of (*y*) by *n* samples to the right, and positive ones by *n* samples to the left. Thus, with increasing *n* from -*N* to *N*, we move (*y*) relative to (*x*) from the right side to the left.

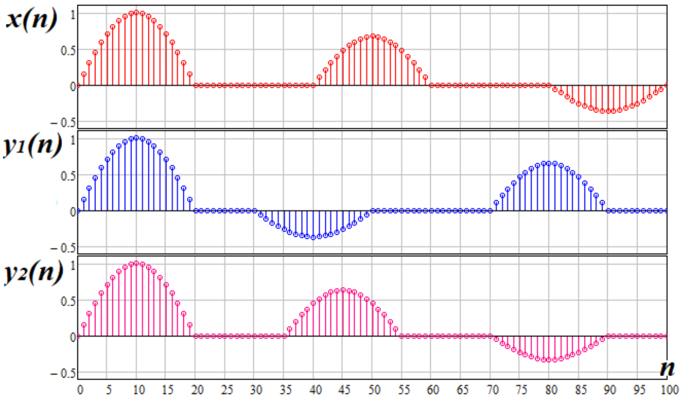

Figure 2: Compared signals

As it can be seen from Fig. 3, the correlation function R_{xx} has the largest value of the maximum, R_{xy2} has a little less value and the smallest value corresponds to R_{xy1}. Thus, computation data results indicate the following: the most similar signal to the signal (*x*) is the signal (*x*) (as expected), from the signals (*y1*) and (*y2*) most similar to the signal (*x*) is (*y2*), that is confirmed by a visual evaluation.

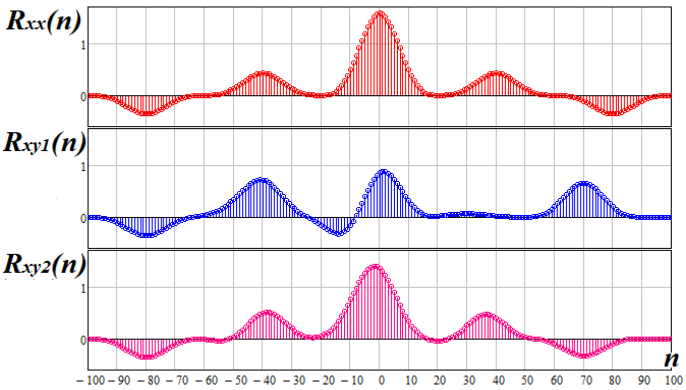

Figure 3: Correlation functions

Thus, it is possible to design an algorithm of TWP recognizing, based on the use of correlation functions. The "measured" TWP will be compared in a certain way with the "reference" TWP, previously simulated by the computer [12-13].

The "measured" TWP may be obtained by digital filtering either the voltage signal or the current signal taken from the secondary leads of the current transformers (in the case of the current signal) or the voltage transformers (in the case of the voltage signal), or the Coupling Capasitor for Power Line Comunications. And it is possible to use a combined signal to extract incident or reflected waves. Also, modal components might be used instead of phase values, for example, the use of only first modal component can reduce the number of measuring systems to one. Modal components are analogue of symmetrical components used in the theory of electromagnetic transient processes. The definition of the modal components is described below [6, 14, 15, 17].

When writing differential equations for a line with distributed parameters with a number of wires greater than 1, instead of 2 equations (for voltage and current), a system of $2n$ equations is obtained (n is the number of wires), which determines the currents and voltages in each wire. When analyzing and solving these equations, for convenience, an incident (or reflected) wave of voltage (or current) is represented as a sum of n incident waves, which are commonly referred to as modes or modal components. Each of these waves is characterized by its own parameters (propagation constant, surge impedance, etc.). Thus, the modal components propagate along their wave (modal) channels with different parameters independently from each other [6, 14].

So, there are n independent wave channels for the n-wire line, each channel covers all or part of the wires. In any case one channel is the channel "all wires to ground" (earth mode) and the other channels are "between-wire" (or phase-to-phase) modes, since the currents in these channels flow mainly along the wires. Thus, there are two phase-to-phase modal channels and one earth modal channel in the case of three-phase line. The first phase-to-phase modal channel is the "middle phase to outside phases" channel (the current flows in one direction through the middle phase and returns through the two outside phases), and the second one is the "outside phase to another outside phase" channel (the current in the forward direction flow through one outside phase and return through another outside phase). The relationship between the phase voltages u_{ph} and currents i_{ph} and the modal voltages u_m and currents i_m is given by [6, 14].

$$[u_m]=[\lambda]^{-1}\cdot[u_{ph}];[i_m]=[\delta]^{-1}\cdot[i_{ph}], \qquad (5)$$

where $[U_{ph}]$, $[U_m]$ – the column matrices, respectively, of the total voltages in the wires and the voltages of the modal components; $[i_{ph}]$, $[i_m]$ – the same for currents; [λ], [δ] – the voltage and current transformation matrices which determine the ratio of the phase and modal quantities.

In the case of three-phase line, the transformation matrices have the form:

$$[\lambda]=\begin{bmatrix} 1 & 1 & 1 \\ \lambda_{2(1)} & 0 & \lambda_{2(0)} \\ 1 & -1 & 1 \end{bmatrix};[\delta]=\begin{bmatrix} 1 & 1 & 1 \\ \delta_{2(1)} & 0 & \delta_{2(0)} \\ 1 & -1 & 1 \end{bmatrix}, \qquad (6)$$

where $\lambda_{2(1)}$, $\lambda_{2(0)}$, $\delta_{2(1)}$, $\delta_{2(0)}$ – coefficients that depend on the line and ground parameters and frequency. These coefficients are usually taken equal to $\lambda_{2(1)} = \delta_{2(1)} = -2$; $\lambda_{2(0)} = \delta_{2(0)} = 1$ [14, 17].

OBTAINING THE "REFERENCE" TWP BY IMITATION SIMULATION

Traveling wave transient processes were modeled in the PSCAD software package. The algorithm of DSP was modeled separately in the Mathcad software.

There was created the model of the investigated HVOCPL "Zhegalovo-Kislorodnaya 2" in the PSCAD, taking into account its real parameters. The schematic image of the HVOCPL is shown in Fig. 1, the PSCAD model is depicted in Fig. 4. The model also includes busbars of adjacent substations, the type and number of connections, as well as load nodes and sources of generation chosen arbitrarily.

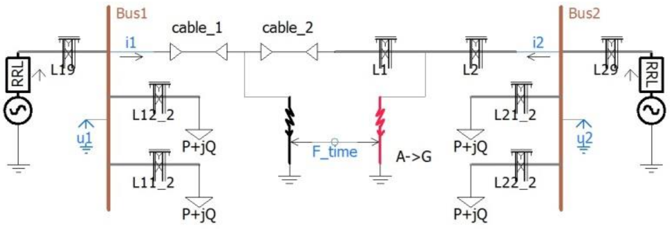

Figure 4: The HVOCPL model in the PSCAD software

All elements of the model are standard components of the program. The overhead lines and cables were modeled by detailed frequency-dependent mathematical models (The Frequency-Dependent (Phase) Model). This model takes into account the dependence of all line parameters on the frequency of the signals. The line is mathematically transformed into three independent single-phase electric circuits, taking into consideration the dependence of the matrix transformation on the frequency [18].

The current and voltage signals calculated in the main PSCAD model then were filtered using the built-in filtering modules (in this case the Butterworth band-pass filter was used), then the modal components were extracted, the first phase-to-phase modal component in this case, which were then recorded on an oscillogram with the certain sample interval (0.5 μs) (see Fig. 5).

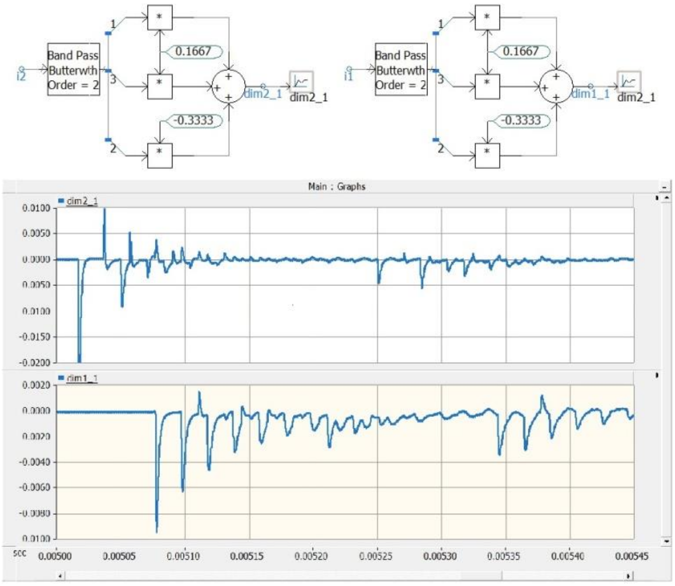

Figure 5: Extraction of the 1 mode current transients and data recording in PSCAD

The 12 fault occurence points were simulated on the cable section and 11 fault occurence points were simulated on the overhead line section in PSCAD. The "reference" TWP were modeled at 100 m intervals along the entire length of the line, and at the distance of up to 500 m along the terminals of each of the sections the overhead and cable steps were reduced to 50 m. The values calculated by the PSCAD program were written with the sample interval 0.5 μs into text files and then processed by the Mathcad software package. Processing of TWP recorded in this way consisted in finding by the algorithm the maximum correlation value among all correlation functions of the "measured" pattern with "reference" patterns.

The detailed description of the algorithms and their performance analysis will be presented in a separate article.

CONCLUSION

The registration of transients during a certain time period at the place of observation (the formation of TWP) can be compared with the sampling of fingerprints of suspects in criminalistics. Just as fingerprints contain unique features for each person, the TWP is unique for each fault occurrence point, and even more so for each faulted section. So as forensics compare fingerprints taken from crime instruments, (often incomplete and damaged) with the data available in the database, the measured TWP in the proposed methods is compared with TWP in the database, simulated earlier.

The proposed approach for identifying the faulted section and the fault location, based on the use of correlation functions, showed good results in the simulation, and the error of these algorithm comprises just 1 step of modeling of the fault occurence point (step of modeling "reference" portraits).

It should be noted that the method of formation and recognizing of TWP can be applied not only to solve the problem of AR of HVOCPL, but also to solve the problem of TWRPA [15]. The improvement of TWRPA fits into the overall concept of "Digital substation" and is one of the most promising directions for the development of modern RPA [1, 9, 11-13, 15].

A further step in the model study of the method will be the introduction of distortions into the simulated signal caused by various kinds of interference, as well as the imperfection of the measuring transducers (current transformers, volage transformers etc).

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